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Swift observation of Segue 1: constraints on sterile neutrino parameters in the darkest galaxy

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ABSTRACT
Some extensions of standard particle physics postulate that dark matter may be partially composed of weakly-interacting sterile neutrino particles that have so far eluded detection. We use a short ($\sim$ 5 ks) archival X-ray observation of Segue 1 obtained with the X-Ray Telescope (XRT) on board the *Swift* satellite to exclude the presence of sterile neutrinos in the 1.6–14 keV mass range down to a flux limit of 6×10^{-12} ergs cm^{-2} s^{-1} within 67 pc of its center. With an estimated mass-to-light ratio of ~ 3400 M$_\odot$/L$_\odot$, Segue 1 is the darkest ultra-faint dwarf galaxy currently measured. Spectral analysis of the *Swift* XRT data fails to find any non-instrumental spectral feature possibly connected with the radiative decay of a dark matter particle. Accordingly, we establish upper bounds on the sterile neutrino parameter space based on the non-detection of emission lines in the spectrum. The present work provides the most sensitive X-ray search for sterile neutrinos in a region with the highest dark matter density yet measured.

Key words: X-rays: general – galaxies: Local Group – cosmology: dark matter – galaxies: individual (Segue 1)

1 INTRODUCTION

The nature of dark matter is possibly the greatest mystery of present-day science. Nearly 80% of the mass density in the Universe cannot be explained with ordinary baryonic matter and requires an additional non-baryonic component aptly named dark matter to reconcile the inferred mass budget (Gaitskell 2004). Barring a radical paradigm shift in fundamental physics, dark matter is expected to encompass one or more species of undiscovered elementary particles that would account for the largest fraction of mass in the Universe. The direct hunt for the culprits is ongoing at various particle physics experiments in the predicted range for supersymmetric particles at center-of-mass energies between 10 GeV and a few TeV (Gaitskell 2004). Indirect dark matter signals from pair annihilations or particle decays are also being sought in a similar range through gamma-ray observations of astrophysical objects with high dark matter density (Aliu et al. 2009; Abdo et al. 2010). However, no significant dark matter signal has been verified (Anderson et al. 2010).

Given our current blindness to the nature of the dark matter particle, it is crucial to span the entire range of hypothesised candidates/signatures of dark matter including those that lie outside the gamma-ray regime. One such possibility is a sterile neutrino, which corresponds to a weakly-interacting fermion associated with the neutrino sector that arise in certain extensions of the standard model (Dodelson & Widrow 1994). A large accumulation of sterile neutrinos in a very compact region could produce a detectable X-ray flux made primarily of particle decays into mono-energetic photons in the 0.1–100 keV energy range (Abazajian, Fuller & Tucker 2001; Dolgov & Hansen 2002; Yüksel, Beacom & Watson 2008). Like other dark matter candidates, any direct or indirect detection of sterile neutrinos will be a challenging but necessary step for our assessment of dark matter in the Universe (Gelmini, Osoba & Palomares-Ruiz 2010).

In order to complete a stringent sterile neutrino search, one would like to target astrophysical objects with the highest dark matter densities. Taken at face value, galaxy clusters should be excellent places to conduct such searches, but their cores are filled with hot emitting interstellar medium that would veil any X-ray trace of a dark matter particle. Similar issues arise in the X-ray emission from massive galaxies that tends to be dominated by hot gas and binary systems. The next best targets may be hiding among the recently discovered population of ultra-faint dwarf galaxies around the Milky Way (Willman et al. 2005; Belokurov et al. 2007). Progress is still being made in characterising the kinematic properties of these objects

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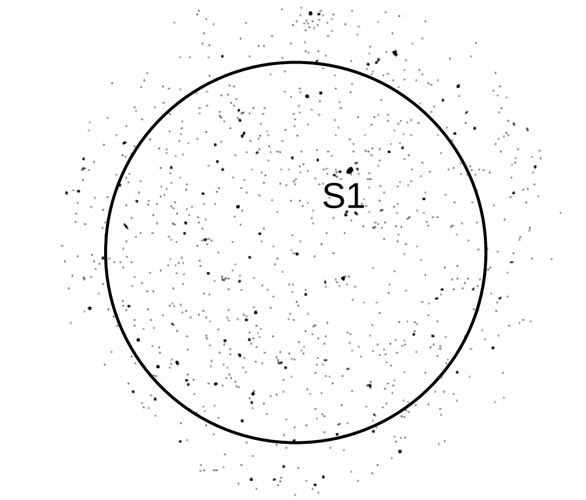

Figure 1. Smoothed *Swift* XRT 0.2–10 keV image of Segue 1. The circle represents the circular extraction region of radius 10′ (67 pc) centered on (J2000.0) RA. $10^{\mathrm{h}}07^{\mathrm{m}}03.^{\mathrm{s}}2$, Dec. $+16°04'25''$. S1 marks the position of SWIFT J100651.4+160845 the single point source in the field detected with signal-to-noise ratio > 5.

(Simon et al. 2010). However, spectroscopic observations suggest that some ultra-faint dwarf galaxies could be the closest and densest dark matter haloes in the Local Group, making them excellent targets to conduct searches for the annihilation or decay of dark matter particles at high energies (Strigari et al. 2008; Simon et al. 2010).

Indirect searches for sterile neutrinos in dwarf galaxies have been conducted in Fornax (Boyarsky et al. 2010), Ursa Minor (Loewenstein, Kusenko & Biermann 2009), and Willman 1 (Loewenstein & Kusenko 2010; Mirabal & Nieto 2010). Out of this group, only Willman 1 falls under the category of ultra-faint dwarf galaxy ($L < 1000 L_{\odot}$) and it is one of the preferred targets for dark matter pursuits (Strigari et al. 2008). However, careful interpretation of Willman 1 has found strong evidence for tidal disruption and possible contamination from foreground stars that could prevent any reliable determination of its dark matter mass from stellar kinematics (Siegel, Shetrone & Irwin 2008; Willman et al. 2010).

In order to sidestep the kinematic complications surrounding Willman 1, we turn to the Milky Way satellite Segue 1 (Belokurov et al. 2007). At a distance of 23 kpc, Segue 1 is the closest ultra-faint dwarf galaxy. With the highest mass-to-light ratio (~ 3400 M$_{\odot}$/L$_{\odot}$) and dark matter density $2.5^{+4.1}_{-1.9}$ M$_{\odot}$ pc^{-3} yet observed, there is general consensus that Segue 1 is the next most promising object for a potential indirect detection of dark matter (Strigari et al. 2008; Simon et al. 2010). In this Letter, we use a *Swift* X-ray observation to constrain the parameter space of sterile neutrinos in Segue 1.

2 OBSERVATION AND X-RAY SOURCE DETECTION

A continuous 4,855 s exposure of Segue 1 was acquired on 2010 February 7 with the X-ray telescope (XRT; Gehrels et al. 2004) on-board the *Swift* satellite. The XRT observation (ID 00031602003) was collected in photon counting (PC) mode with full spectral resolution and a time resolution of 2.5 s. For the analysis, we used the cleaned event file with standard grade filtering (grades 0–12) and default screening parameters in the 0.2–10 keV energy range resulting in an effective exposure time of 4,834 s. Analysis of the data was performed with standard HEAsoft and CIAO tools. Fig. 1 shows the XRT image of the field. The image has been smoothed with a Gaussian kernel $r_k = 7''$. At Galactic coordinates $\ell = 220.5°$, $b = 50.4°$, Segue 1 lies well away from the Galactic plane with Galactic H I column density $N_{\mathrm{H}} = 3.3 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990) and minimal contamination expected from foreground Galactic point sources.

A thorough census of point sources in the field was performed using the Mexican-hat wavelet routine *wavdetect* on scales of 6, 10, and 16 pixels (Freeman et al. 2002). Detections of X-ray point sources required a signal-to-noise ratio > 5. A single source SWIFT J100651.4+160845 (S1) meeting our requirement was found at (J2000) $10^{\mathrm{h}}06^{\mathrm{m}}51.^{\mathrm{s}}4$, Dec. $+16°08'45.3''$ with an uncertainty of 5″. Within a 20 pixel radius centered on SWIFT J100651.4+160845 the 0.3–7 keV count rate is $(4.1 \pm 0.9) \times 10^{-3}$ s^{-1} corresponding to an extrapolated flux in the 0.2–10 keV band of $(1.5 \pm 0.3) \times 10^{-13}$ ergs cm^{-2} s^{-1} with photon index $\Gamma = 2.0$ and $N_{\mathrm{H}} = 3.3 \times 10^{20}$ cm^{-2} as obtained from WebPIMMS [1].

At the derived X-ray position of SWIFT J100651.4+160845, we find SDSS J100651.56+160847.6 a magnitude of $r = 20.1$ optical object that has been photometrically typed as a potential quasi-stellar object (QSO) by the Sloan Digital Sky Survey (SDSS) pipeline (Abazajian et al. 2009). The X-ray point-source catalogue from the *Chandra* Deep Field-South (CDF-S) also predicts at least one background QSO unrelated to Segue 1 to this sensitivity limit for a *Swift* area of ≈ 314 *arcmin*^{2} (Luo et al. 2008). Accordingly, we assign a tentative background QSO classification to SWIFT J100651.4+160845.

3 SPECTRAL ANALYSIS AND STERILE NEUTRINO PARAMETERS

Before extracting the actual spectrum of Segue 1, we excised SWIFT J100651.4+160845 from the event list. We obtained the spectrum using a 10′circle radius centered on the position of Segue 1 (J2000.0) RA. $10^{\mathrm{h}}07^{\mathrm{m}}03.^{\mathrm{s}}2$, Dec. $+16°04'25''$ determined by Martin, de Jong & Rix (2008). The radius corresponds to a physical size of 67 pc at the distance of 23 kpc, equivalent to 2.3 half-light radii (Simon et al. 2010). The resulting spectrum contains 650 net counts in the 0.2–7 keV band. Since the extraction region nearly covers the totality of the *Swift* XRT field, we obviate any background subtraction. We reason that for the desired upper bound on the parameter space of sterile neutrinos of Segue 1, it is better to provide a conservative estimate that includes the background contribution rather than to gamble with an inadequate instrumental background subtraction (see a similar argument by Riemer-Sørensen, Hansen & Pedersen 2006). It is important to note that an extrapolation of the

[1] http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html

counts in the area outside the extraction region indicates that the purported Segue 1 emission has signal-to-noise ratio smaller than 3.

The extracted spectrum was grouped with *grppha* to ensure at least 20 counts per bin. Subsequently, an ancillary response function (ARF) was generated through *xrtmkarf* using the response matrix file (RMF) from the latest distribution in *Swift* Calibration Database[2]. We then fitted the spectrum with a simple absorbed power-law model implemented in XSPEC (Arnaud 1996). Between 0.4 and 5 keV, the spectrum is reasonably fit (reduced $\chi^2 = 1.04$) with a power-law index $\Gamma = 1.4 \pm 0.3$ with $N_{\rm H}$ fixed at the Galactic value. Fig. 2 shows the compounded (source + instrumental background) spectrum of Segue 1 with a power law.

As shown in this Fig. 2, we find no evidence for the presence of emission lines in the compounded spectrum of Segue 1. The main residuals at 0.6 and 2.3 keV between the spectrum and power-law model have been identified with instrumental oxygen and gold edges respectively (Godet et al. 2009). Nickel contamination is also likely present in the 7–8 keV range (Cusumano et al. 2007). For dark matter applications, we find no conclusive evidence of excess emission at ~ 2.5 keV as previously reported in the spectrum of Willman 1 (Loewenstein & Kusenko 2010). However, we must point out that this shorter *Swift* XRT observation was less sensitive and cannot completely rule out a line with flux properties $F_{\rm line} = 3.5 \times 10^{-6}$ ph cm^{-2} s^{-1} claimed by those authors.

In the absence of actual spectral features, the next best thing to do is to produce upper bounds for the sterile neutrino parameter space that directly depend on the upper limits to X-ray counts from emission lines $F_{\rm line}$. For this purpose, we fitted Gaussian lines fixed at a line width $\sigma = 100$ eV between 0.8 and 7 keV using XSPEC. Line emission upper limits were calculated in steps of 0.5 keV over said energy range. We adopt a conservative posture and assume that only line emission (no underlying continuum or instrumental background) contributes to the observed line flux at each energy. In order to convert these measured emission line upper limits into actual points in the sterile neutrino parameter space (mass m_s versus mixing angle θ), we adopt the formalism of Loewenstein & Kusenko (2010),

$$F_{\rm line} = 5.15\ sin^2\theta\ \left(\frac{m_s}{\rm keV}\right)^4 \times f_s {\rm M}_7 {\rm d}_{100}^{-2}\ {\rm ph\ cm^{-2}\ s^{-1}} \quad (1)$$

where sterile neutrinos with mass m_s produce photons at a given line energy $E_{\rm line} = m_s/2$, $\rm M_7$ is the dark matter mass of Segue 1 in units of 10^7 M$_\odot$, f_s is the fraction of dark matter in sterile neutrinos, and $\rm d_{100}$ is the distance to Segue 1 in units of 100 kpc. For the actual calculations, we assume that 100% of dark matter in Segue 1 is composed of sterile neutrinos $f_s = 1$, a helio-centric distance $\rm d_{100} = 0.23$ (Simon et al. 2010), and a dark matter mass $\rm M_7 = 0.06$ (Wolf et al. 2010; Simon et al. 2010). Fig. 3 shows the derived sterile neutrino mass m_s as a function of mixing angle θ. Also shown are the corresponding upper bounds obtained for Willman 1 (Loewenstein & Kusenko 2010; Mirabal & Nieto 2010). It should be noted that there

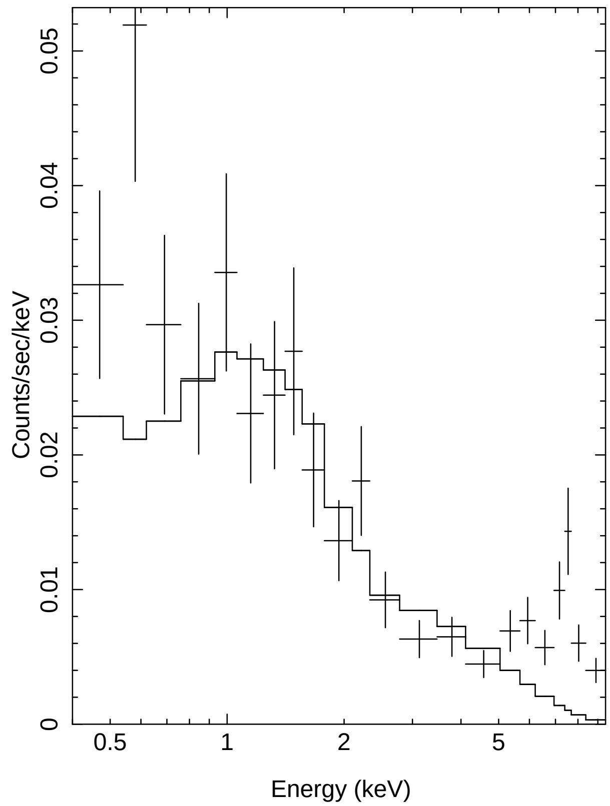

Figure 2. *Swift* XRT spectrum of Segue 1 in the 0.4–10 keV range. The spectral fit correspond to an absorbed power law $\Gamma = 1.4 \pm 0.3$ with Galactic H I column density $N_{\rm H} = 3.3 \times 10^{20}$ cm^{-2}. Excesses at 0.6, 2.3 and 7 keV are likely due to instrumental oxygen, gold, and nickel edges respectively.

is considerable uncertainty on the the dynamic modelling of Willman 1 (Willman et al. 2010).

The constraints for Segue 1 shown in Fig. 3 are about a factor of 10 less sensitive than the upper limits derived for Ursa Minor (Boyarsky et al. 2007). Furthermore, the results are even less restrictive than those reported for the Milky Way (Boyarsky et al. 2007), M31 (Watson et al. 2006), and the unresolved cosmic X-ray background (Abazajian et al. 2007). However, to a large extent, estimates based on Equation (1) depend exclusively on the total dark matter mass $\rm M_7$ rather than specific dark matter densities within the object, which may be more appropriate. At $2.5^{+4.1}_{-1.9}$ M$_\odot$ pc^{-3}, the dark matter density of Segue 1 is significantly (a factor between 2 and 200) higher than that measured in any bound system (Simon & Geha 2007; Weber & de Boer 2010). Assuming that the sterile neutrino line emission has an additional dependence on the dark matter density $n_{\rm dm}$ on small scales, density weighted upper limits could be of similar magnitude.

4 DISCUSSION AND CONCLUSIONS

Based on the observational limits reported here, an unequivocal dark matter signal continues to evade us in the X-ray regime. None the less, by focusing on regions with high dark matter density, we appear to be on the right path to discovery (or exclusion). Because no background subtrac-

[2] http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/

tion was performed on the compounded spectrum of Segue 1, the exclusion region for sterile neutrinos obtained from this observation is less restrictive than previous measurements for similar systems (Loewenstein & Kusenko 2010; Mirabal & Nieto 2010; Boyarsky et al. 2010). Yet, the exercise is valuable as the hunt for an indirect dark matter signal continues from X-ray to gamma-ray energies. It is unfortunate that the observation cannot confirm the presence of the spectral feature claimed in the Willman 1 spectrum because of poorer sensitivity (Loewenstein & Kusenko 2010). However, the reality of this marginal spectral feature remains hotly contested (Boyarsky et al. 2010; Mirabal & Nieto 2010). An additional concern with Willman 1 is the fact that its kinematic properties make it difficult to determine its actual dark matter mass and carry out any subsequent sterile neutrino calculations (Willman et al. 2010).

From the point of view of kinematics, Segue 1 has also faced a serious challenge by Niederste-Ostholt et al. (2009) who argued that the dark matter properties of Segue 1 might be inflated due to possible contamination from stars in the Sagittarius stream. Under the latter interpretation, unrelated field stars would disturb the velocity dispersion measurements and hence inflate the inferred mass-to-light ratio of an otherwise normal stellar cluster. However, recent work counters that with additional stars such possibility is nearly ruled out (Simon et al. 2010). As a result, Segue 1 appears to qualify as the densest dark-matter dominated object with a robust determination of sterile neutrino parameters in the 0.8–7 keV bandpass.

If the high dark matter density value is confirmed with further measurements, Segue 1 will certainly transform itself in the ideal astrophysical laboratory to contrast any direct dark matter particle detection at ground-based accelerators. But any such effort will require that the field of view of Segue 1 is certified as "clean" i.e. void of X-ray/gamma-ray contaminants that might entangle any interpretation of the high-energy emission other than obvious background gamma-ray quiet QSOs. With the discovery of SWIFT J100651.4+160845, we have just begun to probe the X-ray point-source population in the field of Segue 1. Given the potential of novel discoveries, it seems worthwhile to observe Segue 1 with more sensitive X-ray instruments on board the *Chandra* and *XMM-Newton* observatories that could conclusively quantify the contamination from unrelated sources.

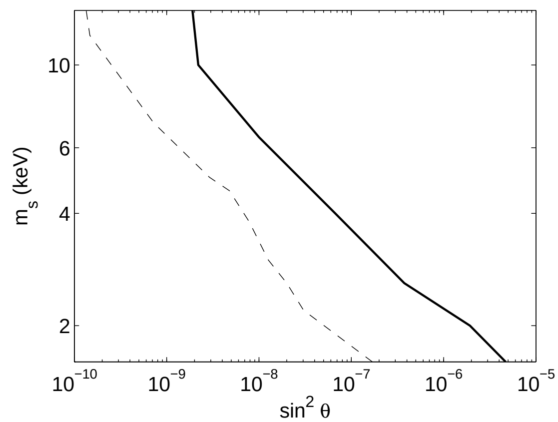

Figure 3. Sterile neutrino parameter space. The thick solid line represents the constraints on sterile neutrinos derived for Segue 1. The thin dashed line corresponds to the upper bound in Willman 1. The parameter space to the right of each line marks the exclusion region assuming 100% of dark matter is composed of sterile neutrinos.

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